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Jelly Roll processed Nb_3Sn wires with improved superconducting performances

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Abstract

Jelly Roll (JR) processed Nb_3Sn wires have been fabricated from laminated composites of Sn-based alloy and Nb sheets. The wires show an offset T_c of 18.1K with a transition width of less than 0.1K, and an offset B_{c2} (4.2K) of 26.5T. The wire keeps B_{c2} of ~13T at 12K. Large non-Cu J_c values have been obtained at 4.2K and above 21T. Relative sheet thickness of the Sn-based alloy and Nb yields significant effect on the structure and J_c of the JR wire.

Keywords: Nb_3Sn wire ; JR process ; Sn-based alloy ; Microstructure ; T_c ; B_{c2} ; J_c

1. Introduction

The Jelly Roll (JR) processed Nb_3Sn wires using Sn-based alloy and Nb sheets have several advantages. The fabrication of resulting wire is quite easy, and the leak out of Sn at the extrusion or heat treatment is prevented by the holding between Nb sheets. Moreover the superconducting performance of the JR-processed wires is at the highest end among different Nb_3Sn wires [1]. In this article the effect of Nb sheet thickness and other parameters on the structure and the performance of JR-processed Nb_3Sn wires will be reported. The increase of Nb sheet thickness has been found to yield significant changes in the structure and critical current density J_c of the wires. The cross-sectional JR configuration in the wire is appreciably improved by the increase of Nb sheet thickness.

2. Experimental

Sn-Ta, Sn-B and Sn-Nb based alloys with different compositions were prepared by a reaction among

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constituent metal powders, at 700 – 750℃ in vacuum. In this article this reaction is called the melt diffusion (MD) of Sn. Tightly consolidated buttons were obtained after the reaction. Several atomic percent of Ti was substituted for Sn, furthermore a small amount of Cu was added to the resulting mixture [1]. Sn-based alloys were pressed into plates followed by rolling to sheets 80μm in thickness. The sheet was laminated with a Nb sheet, 100μm in thickness, and then wound into a JR composite. In addition in this study 160μm-thick Nb sheet has been newly used. The composite was encased in a Nb-3.3at%Ta sheath with outer/inner diameter of 10.0/7.3mm and fabricated into a wire by grooved rolling and subsequent drawing using cassette roller dies. The wires with 1.4, 1.2 and 1.0mm in diameters have been prepared. The fabrication procedure of present JR wires is shown in Fig.1.

The cross-sectional structure of specimens was investigated by optical microscope after anodizing oxidation, and by electron probe microanalyser (EPMA). Areal fraction of the Nb_3Sn layer formed on the cross-section of wires was determined from the EPMA mapping. The transition temperature, T_c, critical current, I_c, and upper critical field, B_{c2} of the wires were measured by a four-probe resistive method. The T_c transition was measured in a transverse field up to 12T. The I_c and B_{c2} were measured in a transverse magnetic field at 4.2K, the criterion of the I_c measurement being 1μV/cm. Non-Cu J_c was calculated by dividing I_c by corresponding cross-sectional area of the wires.

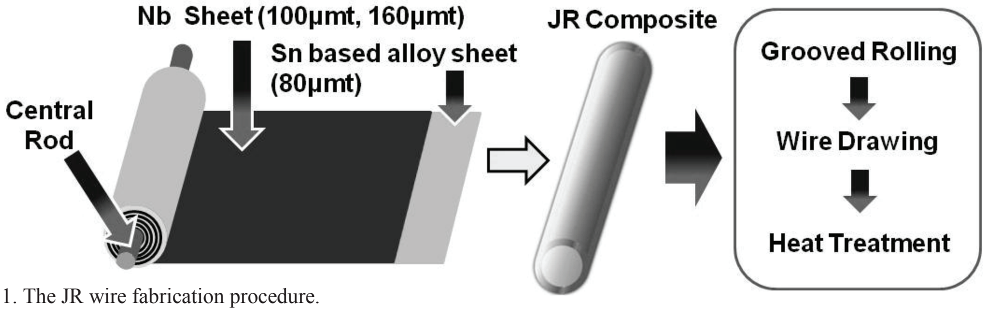

Fig. 1. The JR wire fabrication procedure.

3. Result and Discussion

The role of different elements in the Sn-based alloy is summerized as follows. Ta, B and Nb act as nuclei for the rigid solidification of Sn-based alloy at the MD reaction. Ti yields a tight bonding between Ta, B or Nb particles and Sn matrix, which improves the consolidation and the workability of Sn-based alloys. In addition, Ti enhances the synthesis of Nb_3Sn layer at the heat treatment of the wire. Meanwhile, Cu accelerates the diffusion of Sn as in the bronze-processed wires decreasing the reaction temperature from 900℃ to 725 – 750℃. In the present wires a few wt% Cu addition is enough for this reduction.

Fig. 2 (a) and (b) are the optical micrographs on the cross-section of 8/1(Sn/Ta)-6Ti+3Cu sheet wires heat treated at 750℃ for 100h using 100μm-thick Nb sheet and 160μm-thick Nb sheet, respectively. Above description of composition implies that Sn/Ta atomic ratio is 8/1 where 6at% Ti is substituted for Sn and 3wt% Cu is added to the alloy. In the JR part of the 100μm-thick Nb sheet wire, Nb sheet is completely consumed by the reaction. Abundant Sn diffuses to the sheath and the central core forming thick Nb_3Sn layers. By increasing Nb sheet thickness to 160μm (twice as thick as Sn-based alloy sheet), spiral Nb_3Sn layers are formed in the JR part, while the thickness of Nb_3Sn layer formed on the sheath is much reduced. A small amount of unreacted Nb is present in the JR part. The JR configuration in the wire is appreciably improved by increasing the Nb sheet thickness from 100μm to 160μm.

The Sn concentration in the Nb_3Sn layer formed on the Nb-3.3at% Ta sheath of the 100μm-thick Nb sheet wire is close to the stoichiometry with almost no gradient throughout the layer. About 3at%Ta, which may be substituted for Nb, is present in the Nb_3Sn layer. In the 160μm-thick Nb sheet wire, the Sn concentration in the Nb_3Sn layer decreases to ~22at% again with almost no gradient. In the Nb_3Sn layer

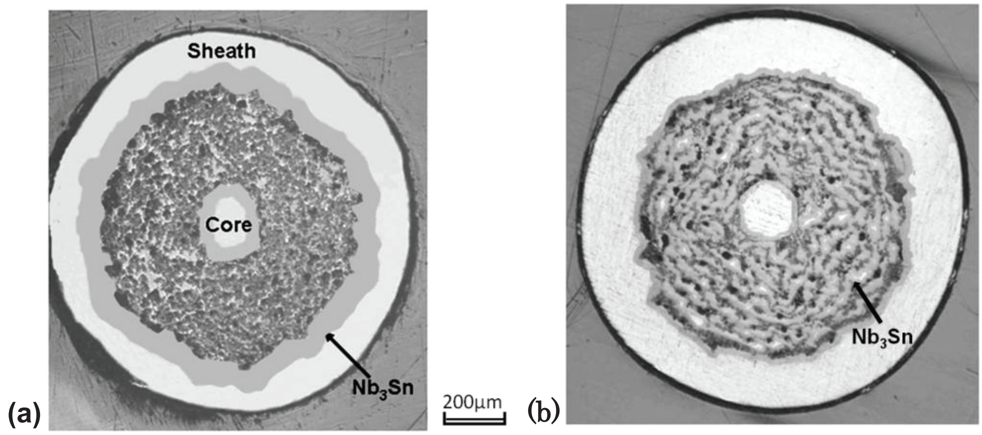

Fig. 2. Optical micrographs on the cross-section of JR wires using 8/1(Sn/Ta)-6Ti+3Cu sheet heat treated at 750℃ for 100h. (a) 100μm-thick Nb sheet wire, (b) 160μm-thick Nb sheet wire. The black ring outside the JR part is the accumulation of Ta, Ti and Cu.

formed in the JR part shown in Fig. 2 (b) no Ta is detected, while ~1at% Ti is incorporated. Ti may be substituted for Sn site.

The SEM structure on the fractured surface of Nb_3Sn layer formed in the 100μm-thick Nb sheet is composed of homogeneous grains with clear boundaries [1]. Meanwhile, in the Nb_3Sn layer formed in the 160μm-thick Nb sheet wire grain boundaries are not clearly seen, however seems to be composed of finer grains. Present study reveals that the thickness of Nb sheet, namely Nb/Sn ratio in the wire, has appreciable effect on the composition and the structure of Nb_3Sn layers.

Fig. 3 (a) illustrates T_c transitions of 4/1(Sn/Ta)-7Ti+2Cu and 16/1(Sn/Nb)-7Ti+3Cu sheet wires up to 12T. The thickness of Nb sheet in the wires is 100μm. At 0T, both wires shows an offset T_c of 18.1K with a transition width of less than 0.1K. At 12T, the offset T_c is ~12.4K with a transition width of ~0.1K. Fig. 2 (b) shows applied magnetic field versus offset T_c of the wires. At 12K, B_{c2} of the wires is still as high as ~13T. This result implies that the present JR Nb_3Sn wires may be useful for refrigerator-cooled superconducting magnets generating 10T at 12K. The offset B_{c2} (4.2K) of these wires have been reported as 26.5T [1].

Fig. 4 illustrates the non-Cu J_c versus magnetic field curves of 8/1 (Sn/Ta)-6Ti+3Cu sheet wire with

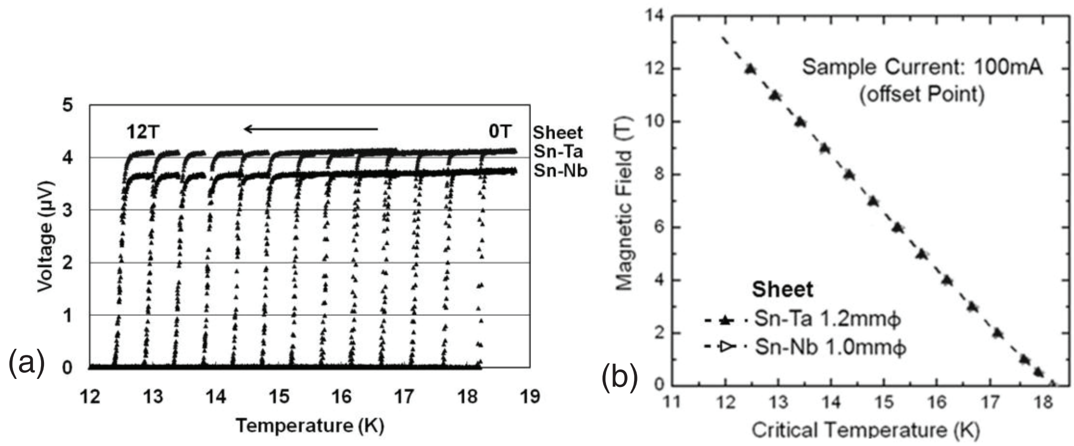

Fig. 3. (a) Magnetic field dependence of T_c transition of 100μm-thick Nb sheet JR wires up to 12T.
(b) Magnetic field versus offset T_c of the wires. Wires were heat treated at 750℃ for 100h.

different diameter and Nb sheet thickness. In the 100μm-thick Nb sheet wire, the non-Cu J_c increases with reducing the wire diameter. This may be originated in the increase of areal fraction of Nb_3Sn layer indicated in the figure. The non-Cu J_c at 4.2K and 22T increases from 120A/mm^2 to 180A/mm^2 by reducing the wire diameter from 1.4mm to 1.0mm.

A pronounced increase of non-Cu J_c with decreasing field is observed in the 160μm-thick Nb sheet wire. The non-Cu J_c at 4.2K of 1.2mmφ wire is ~180A/mm^2 and ~290A/mm^2 at 22T and 21T, respectively. Since the non-Cu J_c of 1.0mmφ wires with 160μm-thick Nb sheet has not yet been measured, still better non-Cu J_c may be expected. The 160μm-thick Nb sheet wires, 1.2mmφ and 1.4mmφ in diameter, show offset T_c of 18.0K with a transition width of less than 0.1K.

The difference in non-Cu J_c versus magnetic field curves between 100μm-thick and 160μm-thick Nb sheet wires may be originated in the difference in the structure of Nb_3Sn layer described above. Finer Nb_3Sn grains in the 160μm-thick Nb sheet wires may produce larger J_c in lower fields. Furthermore in the 100μm-thick Nb sheet wire the current may be mostly carried by the thick Nb_3Sn layers containing ~3at% Ta formed on the sheath, while in the 160μm-thick Nb sheet wire the Nb_3Sn layers formed in the JR part containing ~1at% Ti and no Ta may be responsible for the current transport. The difference in the non-Cu J_c versus magnetic field performance between both wires may be also caused by the difference in the third element. The Ta addition yields larger J_c in very high fields above 22T, while the Ti addition may enhance J_c more effectively than the Ta addition in lower fields.

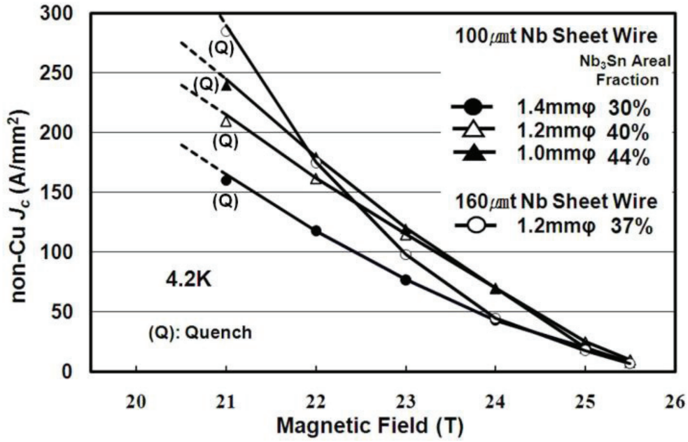

Fig. 4. Non-Cu J_c versus magnetic field curves of wires reacted at 750℃ for 100h with different diameter and Nb sheet thickness, the composition of Sn-based alloy sheet being 8/1(Sn/Ta)-6Ti+3Cu. Areal fraction of Nb_3Sn in the wire is indicated in the figure.

4. Conclusion

Offset T_c of 18.1K, offset B_{c2} (4.2K) of 26.5T and offset B_{c2} (12K) of 13T have been obtained in the JR wires with 100μm-thick Nb sheet and 80μm-thick Sn-based alloy sheet. Reducing wire diameter increases the non-Cu J_c may be due to the increase of the Nb_3Sn areal fraction. Increase of Nb sheet thickness to 160μm yields significant changes in the structure and the non-Cu J_c-B performance. A non-Cu J_c of ~290A/mm^2 has been obtained at 4.2K and 21T for the 1.2mmφ wire. Present JR-processed new Nb_3Sn wires may be promising for high-field magnets as well as for refrigerator-cooled magnets.

Reference

[1] K. Tachikawa, T. Ando, H. Sasaki, M. Yamaguchi and T. Takeuchi, IEEE Trans. Appl. Supercond. 21 (2011) 2533.